**Importance in Relation to ASCE 7-05**

- Derivation and explanation of the *response reduction factor, R*
- Derivation and explanation of the *displacement amplification factor, C_d*
- Derivation and explanation of the *overstrength factor, Ω_o*

**Inelastic Behavior of Structures**

From material to cross section to critical region to structure

**Idealized Inelastic Behavior**

From material.....

![Idealized Inelastic Behavior Diagram]

**Stress-Strain Relationships for Steel**

![Stress-Strain Graph]
Stress-Strain Relationships for Steel

Concrete Confinement

Benefits of Confinement

Idealized Inelastic Behavior

Strain Stress Moment

ε

σ

My

φ

ε

σ

Mu

ELASTIC

INELASTIC

Olive View Hospital, 1971 San Fernando Valley earthquake
NOTE: $\mu_\phi \leq \mu_\theta$

NOTE: $\mu_\pi \leq \mu_\theta \leq \mu_\phi$

Note:

$\mu_\Lambda \leq \mu_\eta$
Loss of Ductility Through Hierarchy

Strain $\mu_e = 100$
Curvature $\mu_q = 12$ to $20$
Rotation $\mu_\theta = 8$ to $14$
Displacement $\mu_\Delta = 4$ to $10$

Ductility and Energy Dissipation Capacity

- System ductility of 4 to 6 is required for acceptable seismic behavior.
- Good hysteretic behavior requires ductile materials. However, ductility in itself is insufficient to provide acceptable seismic behavior.
- Cyclic energy dissipation capacity is a better indicator of performance.

Response Under Reversed Cyclic “Loading”

Earthquakes impose DEFORMATIONS. Internal forces develop as a result of the deformations.

Laboratory Specimen under Cyclic Deformation Loading

Deformations are cyclic, inelastic, and “reversed”

Hysteretic Behavior

ROBUST (Excellent)
PINCHED (Good)
Ductility and Energy Dissipation Capacity

• The structure should be able to sustain several cycles of inelastic deformation without significant loss of strength.

• Some loss of stiffness is inevitable, but excessive stiffness loss can lead to collapse.

• The more energy dissipated per cycle without excessive deformation, the better the behavior of the structure.

Why Is Inelastic Response Necessary?

Compare the Wind and Seismic Design of a Simple Building

Wind:

100 mph fastest Exposure C
Velocity pressure \( q_v = 25.6 \) psf
Gust/exposure factor \( C_g = 1.25 \)
Pressure coefficient \( C_p = 1.3 \)
Load factor for wind = 1.3

Total wind force on 120-foot face:
\[ V_{W120} = 62.5 \times 120 \times 25.6 \times 1.25 \times 1.3 \times 1.3 / 1000 = 406 \text{ kips} \]

Total wind force on 90-foot face:
\[ V_{W90} = 62.5 \times 90 \times 25.6 \times 1.25 \times 1.3 \times 1.3 / 1000 = 304 \text{ kips} \]
Earthquake:

Building weight, $W = 120 \times 90 \times 62.5 \times 8/1000 = 5400$ kips

$$V_{EQ} = C_s W$$

$$C_s = \frac{S_{eq}}{T(R/I)} = \frac{0.48}{1.0(1.0/1.0)} = 0.480$$

Total **ELASTIC** earthquake force (in each direction):

$$V_{EQ} = 0.480 \times 5400 = 2592 \text{ kips}$$

Comparison: Earthquake vs. Wind

- ELASTIC earthquake forces 6 to 9 times wind!
- Virtually impossible to obtain economical design

Comparison: Earthquake vs. Wind

$$V_{EQ} = \frac{2592}{406} = 6.4$$

$$V_{W120} = \frac{2592}{304} = 8.5$$

How to Deal with Huge Earthquake Force?

- Isolate structure from ground (base isolation)
- Increase damping (passive energy dissipation)
- Allow controlled inelastic response

Historically, building codes use **inelastic response procedure**. Inelastic response occurs through structural **damage** (yielding). We must control the damage for the method to be successful.

Assume Frame Is Designed for Wind

“Pushover” Analysis Predicts Strength = 500 k

<table>
<thead>
<tr>
<th>Force, kips</th>
<th>Displacement, inches</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>2.0</td>
</tr>
<tr>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>5.0</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Idealized SDOF Model

- $F_y = 500 \text{ k}$
- $\xi = 11 \%$
- $K_0 = 550 \text{ kips/ft}$

El Centro Ground Motion

Response Computed by NONLIN

- Maximum displacement: 4.79 in.
- Maximum shear force: 542 k
- Number of yield events: 15
Inelastic Behaviors 6 - 37

**Response Computed by NONLIN**

Yield displacement = 500/550 = 0.91 inch

Ductility Demand = \[
\text{Maximum Displacement} / \text{Yield Displacement} = \frac{4.79}{0.91} = 5.26
\]

Interim Conclusion (The Good News)

The frame, designed for a wind force that is 15% of the ELASTIC earthquake force, can survive the earthquake if:

- It has the capability to undergo numerous cycles of INELASTIC deformation.
- It has the capability to deform at least 5 to 6 times the yield deformation.
- It suffers no appreciable loss of strength.

**REQUIRES ADEQUATE DETAILING**

Interim Conclusion (The Bad News)

As a result of the large displacements associated with the inelastic deformations, the structure will suffer considerable structural and nonstructural damage.

- This damage must be controlled by adequate detailing and by limiting structural deformations (drift).

Development of “Equal Displacement” Concept of Seismic Resistant Design

Concept used by:

- IBC
- NEHRP
- ASCE-7

In association with "force based" design concept. Used to predict design forces and displacements

- FEMA 273

In association with static pushover analysis. Used to predict displacements at various performance points.

The Equal Displacement Concept

“The displacement of an inelastic system, with stiffness \( k \) and strength \( F_y \), subjected to a particular ground motion, is approximately equal to the displacement of the same system responding elastically.”

(The displacement of a system is independent of the yield strength of the system.)

Repeat Analysis for Various Yield Strengths (All other parameters stay the same)
Constant Displacement Idealization of Inelastic Response

ACTUAL BEHAVIOR

IDEALIZED BEHAVIOR

0 2 4 6 8 0 2 4 6 8
Displacement, Inches
Displacement, Inches

Force, Kips
Force, Kips

For design purposes, it may be assumed that inelastic displacements are equal to the displacements that would occur during an elastic response.

The required force levels under inelastic response are much less than the force levels required for elastic response.

Equal Displacement Idealization of Inelastic Response

For design purposes, it may be assumed that inelastic displacements are equal to the displacements that would occur during an elastic response.

The required force levels under inelastic response are much less than the force levels required for elastic response.

Equal Displacement Concept of Inelastic Design

Elastic
Inelastic

Ductility supply MUST BE > ductility demand = \frac{\mu}{0.91} = 6.34

ASCE 7 Approach

Use basic elastic spectrum but, for strength, divide all pseudoacceleration values by \( R \), a response modification factor that accounts for:

- Anticipated ductility supply
- Overstrength
- Damping (if different than 5% critical)
- Past performance of similar systems
- Redundancy
First Significant Yield is the level of force that causes complete plastification of at least the most critical region of the structure (e.g., formation of the first plastic hinge).

The design strength of a structure is equal to the resistance at first significant yield.

Sources of Overstrength

- Sequential yielding of critical regions
- Material overstrength (actual vs specified yield)
- Strain hardening
- Capacity reduction ($\phi$) factors
- Member selection
**Definition of Overstrength Factor \( \Omega \)**

\[
\Omega = \frac{\text{Apparent Strength}}{\text{Design Strength}}
\]

- Force
- Apparent Strength
- Design Strength
- Overstrength
- Displacement

**Definition of Ductility Reduction Factor \( R_d \)**

\[
R_d = \frac{\text{Elastic Strength Demand}}{\text{Apparent Strength}}
\]

- Force
- Elastic Strength Demand
- Apparent Strength
- Overstrength
- Displacement

**Definition of Response Modification Coefficient \( R \)**

\[
R = \frac{\text{Elastic Strength Demand}}{\text{Design Strength}} = R_d \Omega
\]

- Overstrength Factor \( \Omega \)
- Ductility Reduction \( R_d \)
- \( R \)

**Definition of Deflection Amplification Factor Coefficient \( C_d \)**

- Computed Design Displacement Demand \( \Delta_D \)
- Actual Inelastic Displacement Demand \( \Delta_I \)
- Elastic Displacement Demand \( \Delta_E \)

- \( C_d \)
- Computed Design Displacement Demand
- Actual Inelastic Displacement Demand
- Elastic Displacement Demand
- \( \text{ANALYSIS DOMAIN} \)
ASCE 7 Approach for Displacements

Determine design forces: \( V = C_s W \), where \( C_s \) includes ductility/overstrength reduction factor \( R \).

Distribute forces vertically and horizontally and compute displacements using linear elastic analysis.

Multiply computed displacements by \( C_d \) to obtain estimate of true inelastic response.

Examples of Design Factors for Steel Structures

ASCE 7-05

<table>
<thead>
<tr>
<th>Group</th>
<th>( R )</th>
<th>( \Omega_o )</th>
<th>( R_d )</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Moment Frame</td>
<td>8</td>
<td>3</td>
<td>2.67</td>
<td>5.5</td>
</tr>
<tr>
<td>Intermediate Moment Frame</td>
<td>4.5</td>
<td>3</td>
<td>1.50</td>
<td>4.0</td>
</tr>
<tr>
<td>Ordinary Moment Frame</td>
<td>3.5</td>
<td>3</td>
<td>1.17</td>
<td>3.0</td>
</tr>
<tr>
<td>Eccentric Braced Frame</td>
<td>8</td>
<td>2</td>
<td>4.00</td>
<td>4.0</td>
</tr>
<tr>
<td>Eccentric Braced Frame (Pinned)</td>
<td>7</td>
<td>2</td>
<td>3.50</td>
<td>4.0</td>
</tr>
<tr>
<td>Special Concentric Braced Frame</td>
<td>6</td>
<td>2</td>
<td>3.00</td>
<td>5.0</td>
</tr>
<tr>
<td>Ordinary Concentric Braced Frame</td>
<td>3.25</td>
<td>2</td>
<td>1.25</td>
<td>3.25</td>
</tr>
<tr>
<td>Not Detailed</td>
<td>3</td>
<td>3</td>
<td>1.50</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Note: \( R_d \) is ductility demand ONLY IF \( \Omega_o \) is achieved.

Examples of Design Factors for Reinforced Concrete Structures

ASCE 7-05

<table>
<thead>
<tr>
<th>Group</th>
<th>( R )</th>
<th>( \Omega_o )</th>
<th>( R_d )</th>
<th>( C_d )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special Moment Frame</td>
<td>8</td>
<td>3</td>
<td>2.67</td>
<td>5.5</td>
</tr>
<tr>
<td>Intermediate Moment Frame</td>
<td>5</td>
<td>3</td>
<td>1.67</td>
<td>4.5</td>
</tr>
<tr>
<td>Ordinary Moment Frame</td>
<td>3</td>
<td>3</td>
<td>1.00</td>
<td>2.5</td>
</tr>
<tr>
<td>Special Reinforced Shear Wall</td>
<td>5</td>
<td>2.5</td>
<td>2.00</td>
<td>5.0</td>
</tr>
<tr>
<td>Ordinary Reinforced Shear Wall</td>
<td>4</td>
<td>2.5</td>
<td>1.60</td>
<td>4.0</td>
</tr>
<tr>
<td>Detailed Plain Concrete Wall</td>
<td>2</td>
<td>2.5</td>
<td>0.80</td>
<td>2.0</td>
</tr>
<tr>
<td>Ordinary Plain Concrete Wall</td>
<td>1.5</td>
<td>2.5</td>
<td>0.60</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Note: \( R_d \) is ductility demand ONLY IF \( \Omega_o \) is achieved.

Using Modified ASCE 7 Spectrum to Determine Force Demand

\( V = 0.15W \)

Using Modified ASCE-7 Spectrum to Determine Displacement Demand

\( C_d = 3.5 \)
Displacements must be multiplied by factor $C_d$ because displacements based on reduced force would be too low.

$$\Delta_{\text{INELASTIC}} = C_d \times \Delta_{\text{REDUCED ELASTIC}}$$

```
\begin{align*}
\Delta_{\text{INELASTIC}} & = 3.65 \text{ in.} \\
C_d & = 3.5
\end{align*}
```

“Equal displacement” approach may not be applicable at very low period values.

```
\[ E_i = F_i \delta_y - 0.5F_i \delta_u = F_i \delta_y (\mu - 0.5) \]
```

### Equal Energy Concept (Applicable at Low Periods)

ELASTIC ENERGY

\[ E_E = 0.5 \frac{F_E}{F_I} \delta_y = 0.5 \delta_y \frac{F^2}{F_I} \]

INELASTIC ENERGY

\[ E_i = F_i \delta_y - 0.5F_i \delta_u = F_i \delta_y (\mu - 0.5) \]

### Equal Energy Concept (Applicable at Low Periods)

Assuming $E_E = E_i$:

\[ \frac{F_E}{F_I} = \sqrt{2\mu - 1} \]

### Newmark Inelastic Spectrum (for Pseudoacceleration)

Elastic:

Inelastic:

Equal Disp

Equal Energy

Transition

```
\begin{align*}
\text{Pseudo Velocity, in/sec} \\
\text{Period, Seconds}
\end{align*}
```

```
\begin{align*}
F_i = \frac{F_e}{2\mu - 1} \\
F_i \Delta \mu
\end{align*}
```
Newmark’s Inelastic Design Response Spectrum

To obtain inelastic displacement spectrum, multiply the spectrum shown in previous slide by $\mu$ (for all periods).

At very low periods, the ASCE 7 spectrum does not reduce to ground acceleration so this partially compensates for “error” in equal displacement assumption at low period values.

Note: FEMA 273 has explicit modifications for computing “target at low periods.”